Effects of Anxiety and Cognitive Load on Instrument Scanning Behavior in a Flight Simulation

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ABSTRACT

Previous research has rarely examined the combined influence of anxiety and cognitive load on gaze behavior and performance whilst undertaking complex perceptual-motor tasks. In the current study, participants performed an aviation instrument landing task in neutral and anxiety conditions, while performing a low or high cognitive load auditory *n*-back task. Both self-reported anxiety and heart rate increased from neutral conditions indicating that anxiety was successfully manipulated. Response accuracy and reaction time for the auditory task indicated that cognitive load was also successfully manipulated. Cognitive load negatively impacted flight performance and the frequency of gaze transitions between areas of interest. Performance was maintained in anxious conditions, with a concomitant decrease in *n*-back reaction time suggesting that this was due to an increase in mental effort. Analyses of individual responses to the anxiety manipulation revealed that changes in anxiety levels from neutral to anxiety conditions were positively correlated with changes in visual scanning entropy, which is a measure of the randomness of gaze behavior, but only when cognitive load was high. This finding lends support for an interactive effect of cognitive anxiety and cognitive load on attentional control.

Index Terms: scanpath, entropy, eye-movement, anxiety, workload, instrumentation, visuomotor performance

1 INTRODUCTION

Complex instrument displays are a common feature of high-anxiety, high-workload environments such as in an aircraft cockpit or chemical plant operation. Each instrument visually represents critical information that is constantly updated, which has to be monitored by and communicated to the human operator. In the case of aviation control, instruments provide the only source of reliable information for flight control under low visibility conditions. In this paper, we demonstrate how instrument scanning planning can be compromised by a user's state of anxiety and load. This reflects the role that cognition plays in controlling eye-movement behavior for information updating. Although we specifically investigated scanning behaviour in the context of a simulated fixed-wing landing task, these results have general implications for the design of visual instrumentation for high-anxiety, high-workload environments.

How do we seek out visual information across multiple regions-of-interest (i.e., instruments)? It has been argued that two attentional sub-systems control information-seeking behavior, a goal-directed system and a stimulus-driven system [1]. The goal-directed system directs attention based on current goals, task knowledge and predictions. In contrast, the stimulus driven system directs attention based on salient sensory events. Attentional control theory (ACT) [2] suggests that anxiety can result in an increased prioritization of the stimulus-driven system over the goal-directed system. The effects of anxiety on attentional control can be further exacerbated when the goal-directed system is further burdened by cognitively demanding tasks [3], such as those that impose a working memory load (e.g., *n*-back matching task). In other words, anxiety and cognitive load can severely hamper one's goal to systematically scan instruments and retrieve critical information, resulting in apparently random patterns of instrument scanning behavior.

A number of studies have found supporting evidence for the predictions of ACT on gaze behavior [4, 5, 6, 7, 8]. Anxiety has been shown to increase the frequency of fixations on goal-irrelevant stimuli [8] and to reduce the duration of ordinarily long target-focused fixations [5, 9, 7]. Recently, two studies have examined the effects of anxiety on gaze behavior in aviation tasks [10, 11]. Allsop and Gray [10] asked participants to perform a flight landing task in neutral and anxiety conditions after extensive practice. They found that that anxiety led to a higher proportion of eye-movement dwells on the outside world and a lower proportion on cockpit instruments. Also, anxiety increased the randomness of gaze behavior patterns. Vine and colleagues [11] examined the stress appraisals of commercial airline pilots before undertaking an important periodic proficiency exam. Pilots who appraised the exam as being more threatening exhibited higher search rates and more fixations on unimportant regions of the cockpit. Such evaluations were also marginally related to increases in scanning randomness.

Although a number of simple laboratory tasks have suggested that the effects of anxiety are exacerbated when cognitive load is high [12, 13, 14], relative few studies have explored this prediction in a complex environment wherein operation performance relies heavily and continuously on instrument scanning behavior. In this current work, we trained participants to perform a simulated flight landing task under instrument flight rules in a fixed-base flight simulator. Under foggy conditions, participants had to rely entirely on their ability to scan instruments for flight control and to do so in a sys-

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tematic fashion. During testing, we induced anxiety and introduced a secondary cognitive load task. The former manipulation was validated with subjective and physiological measurements. We predicted that instrument scanning behavior would be more random as a result of both manipulations. Furthermore, individuals can react differently in anxiety-inducing situations, therefore we predicted that changes in anxiety would correlate with changes in scanning randomness, and that a stronger relationship would be found under high cognitive load. This would suggest that one's psychological state has a significant impact on information-seeking behavior. We propose that patterns of information-seeking behavior on visual instrumentation could be analyzed in the future as a metric for assessing user anxiety and cognitive workload.

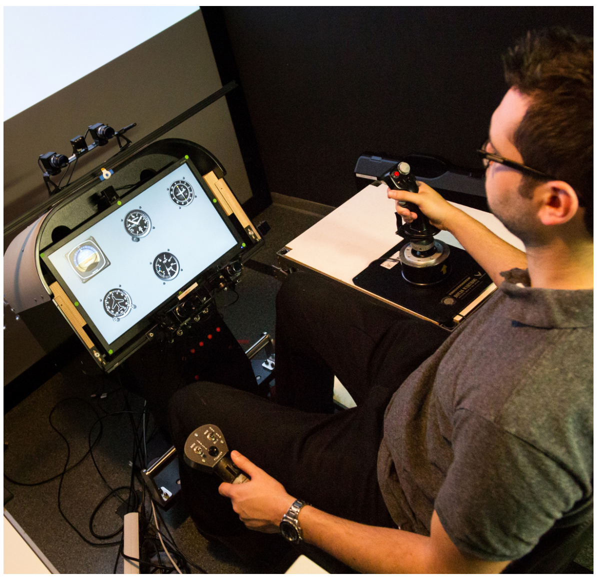

Figure 1: . Photograph of the experimental setup showing the heads-down instrument panel, back-projection screen, control devices and eye-tracking cameras

2 METHOD

2.1 Apparatus

X-Plane 10 (Laminar Research) was used to simulate all landings, with flight data being recorded at 52Hz. The external scene was displayed on the upper half (0.96 m) of a large (2.20 x 1.92 m; 1400 x 1050 pixels) back-projected screen (Christie Mirage S+3K DLP; 101 Hz). A TFT monitor (45 x 25cm; 1600 x 1900 pixels) was used to display an instrument panel consisting of five electromechanical style instruments, namely: attitude indicator (AI), altimeter (Alt), instrument landing system course deviation indicator (ILS), heading indicator (Hdg) and vertical speed indicator (VSI). The viewing distance for the projection screen and heads-down monitor were 1.8 and 1.0 m, respectively (see Figure 5.1). The roll and pitch axes of a simulated aircraft (Cirrus Vision SPF50) were controlled by the participants right hand using a Thrustmaster HOTAS Warthog joystick (Guillemot, Montreal, Canada). Auto throttles maintained indicated airspeed at 51.4 m s-1 (100 knots). A remote video-based eyetracking (faceLAB; Seeing-Machines) system was used to record eye movements (precision $< 1.0^\circ$) at a rate of 60 Hz. A pair of headphones (Beyerdynamic DT770 Pro) were used to deliver the cognitive load task. To respond to the cognitive load task, participants used their left hand to push a button on a custom-made USB collective joystick.

2.2 Task

The task required participants to land an aircraft by accurately following an ideal approach path to the runway in instrument meteorological conditions (visibility=1.2 km). Participants therefore needed to use cockpit instruments in order to follow the ideal path. The ideal path is comprised of both a 3° vertical plane, and the lateral component is simply an extension of the runway centreline. At the start of each landing trial, the aircraft was positioned and orientated 6 nautical miles away from the runway, on the ideal approach path. Wind speed was set to 20 knots for all trials, however, the direction was varied based on the experimental phase, as further detailed below. Numerical and graphical error feedback was presented after each trial.

2.3 Measures

State Anxiety and Heart Rate State anxiety was measured after each flight in the experimental phase using the cognitive anxiety subscale (5 items) of the previously validated Competitive State Anxiety Inventory 2-revised [15]. Heart rate was measured using a chest-strap heart rate monitor (Garmin Model HRM1G) to provide confirmatory physiological evidence of the effectiveness of the anxiety manipulation. Data was recorded during each experimental trial at a rate of 1 Hz.

Gaze Behavior Horizontal and vertical screen coordinates on both the external world and instrument panel were converted into fixations using a dispersion threshold identification algorithm [16]. The minimum fixation threshold was set to 150 ms as per similar research [17]. Fixations were assigned to six areas of interest (external world and the five instruments), based on the AOI screen coordinates. These data were used to calculated AOI transiton frequency, and scanning entropy, which indicates the randomness of scanning behavior, for more information see [10, 18].

Performance Similar to previous studies studies [10, 19, 20] root mean square error (RMSE) of the vertical deviation from the ideal 3° glideslope was used as the performance metric. In X-Plane, one glideslope dot represents a 0.28° error.

2.4 Participants

Sixteen participants (11 Male, 5 Female; mean age = 26.6, SD = 3.8) completed the experiment. Ethical approval was granted by a university ethics committee and informed consent was gained from all.

2.5 Procedure

Each participant visited the lab on two occasions separated by a maximum of one week, with each session lasting approximately two hours. The experiment was split into an acquisition phase which was then followed by an experimental phase.

Acquisition phase Participants completed a total of 22 acquisition trials. In order to ensure that participants used the cockpit instruments, rather than adopting a similar movement strategy for each trial, the simulated wind was randomly set (chosen from one of 4 angles: 20, 160, 200 and 340°), except for the final three acquisition trials, where wind was set to 160°.

Table 1: Mean (SD) *n*-back percentage correct, *n*-back reaction time, flight performance, transition frequency and scanning entropy in neutral and anxiety conditions and low and high cognitive load conditions

	Neutral Conditions		Anxiety Conditions	
	Low Cognitive Load	High Cognitive Load	Low Cognitive Load	High Cognitive Load
N-back: Percentage Correct	91.33 (2.50)	74.56 (3.40)	91.0 (4.03)	76.06 (4.76)
N-back: Reaction Time (ms)	766.87 (44.51)	778.98 (32.60)	686.35 (24.14)	723.79 (30.89)
Glideslope RMSE (Dots)	0.46 (0.27)	0.53 (0.35)	0.44 (0.23)	0.53 (0.26)
Transition Frequency	187.81 (27.45)	169.63 (36.53)	188.88 (33.68)	166.50 (34.59)
Scanning Entropy (Bits)	1.38 (0.18)	1.41 (0.18)	1.44 (0.20)	1.40 (0.19)

Experimental phase In the experimental phase, both state anxiety and cognitive workload was manipulated in a 2 cognitive load (Low, High) x 2 anxiety condition (Neutral, Anxiety) within-subjects design (for further details, see the cognitive load and anxiety manipulation sections below). The order of these trials was counterbalanced across participants. The ordering of cognitive load conditions was also counterbalanced across participants, the ordering was the same in neutral and anxiety conditions. It was emphasised that both tasks were of equal importance. Wind direction was set to 160° for all trials.

Cognitive load manipulation An auditory *n*-back task [21] was used to manipulate cognitive load. This task consisted of a series of stimuli (spoken consonants) that were sequentially played at an interstimulus interval of two seconds [22]. For each stimulus, the participant was instructed to respond as quickly and accurately as possible if it was a target. In the low cognitive load condition, n was set to 0. In the high cognitive load condition, n was set to 2. Across both conditions, 25 % of stimuli were targets. Reaction time and percentage accuracy were measured.

Anxiety Manipulation Anxiety was manipulated using a combination of monetary incentives and ego-threatening instructions, similar manipulations have previously been shown to successfully increase anxiety in a variety of other experiments [10, 23, 24]. Briefly, for neutral, low-anxiety trials the instruction to participants was simply to perform the best they can. For high-anxiety trials, the manipulation consisted of three components. Firstly, a leaderboard and €50 monetary prize for the best combined performance across both anxiety trials. Participants were told that the leaderboard would be e-mailed to other participants at the end of the study. Secondly, a video camera (Sony DCR-TRV890E) was overtly set-up behind the participant, they were informed that recordings of their trials could potentially be used in upcoming presentations and lectures based on their performance. Thirdly, participants were also told that they would be flying in an online virtual environment called the Virtual Air Traffic Simulation Network (www.vatsim.net). A custom-made program was made to give the appearance of 'logging-in' to the network and world mapping program was integrated, this showed a top-down view of the airport and was populated with aircraft.

3 Results

A subsection of the data are presented in this paper, separate (2 Anxiety condition x 2 Cognitive load) repeated measures ANOVAs were carried out with partial eta squared used an indicator of effect size, significant effects were explored using Tukey's HSD post-hoc procedures ($p<0.05$).

In line with our hypothesis and previous research [10, 25] we examined whether individual responses to the anxiety manipulation may be related to scanning entropy, and whether cognitive load may moderate this relationship. Similar to within-subject moderation procedures [26], difference scores between neutral conditions and anxiety conditions for both low- and high cognitive load conditions, were created for the state anxiety and entropy data. A correlated but non-overlapping comparison procedure (see [27]) was used to determine if cognitive load moderated the relationship between change in entropy and change in anxiety.

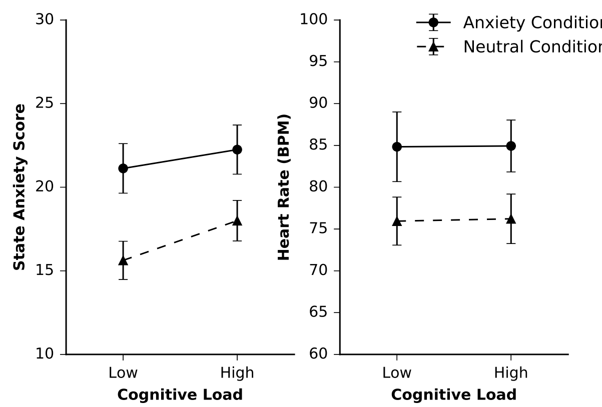

Figure 2: Mean state anxiety (left panel) and heart rate (right panel) plotted as a function of cognitive load in neutral (dashed line) and anxiety (solid line) conditions. Error bars represent standard errors of the mean

Anxiety manipulation check Anxiety manipulation check data are displayed in Figure 2. For heart rate data, the analyses revealed a significant main effect for anxiety condition $F(1,15)=18.07$, $p=.001$, $\eta_p^2=.55$. Post-hoc tests revealed that heart rate was significantly higher in anxiety conditions. For state anxiety data, significant main effects for anxiety condition, $F(1,15)=10.19$, $p=.006$, $\eta_p^2=.41$, and cognitive load, $F(1,15)=6.62$, $p=.02$, $\eta_p^2=.31$. Participants experienced significant increases in state anxiety in both the anxiety and high cognitive load conditions.

Cognitive load Table 1 displays data from the *n*-back task. Data from two low workload trials were lost due to a computer malfunction, these participants were removed from the analyses. For percentage correct data, a main effect for cognitive load was found, $F(1,13)=49.59$, $p<.001$, $\eta_p^2=.79$. The high cognitive load (2-back) was more difficult, with significantly more incorrect responses being made. Analysis of reaction time data revealed a significant main effect for anxiety condition $F(1,13)$=7.64, p=.016, η_p^2=.37. Reaction time was significantly shorter in anxiety conditions.

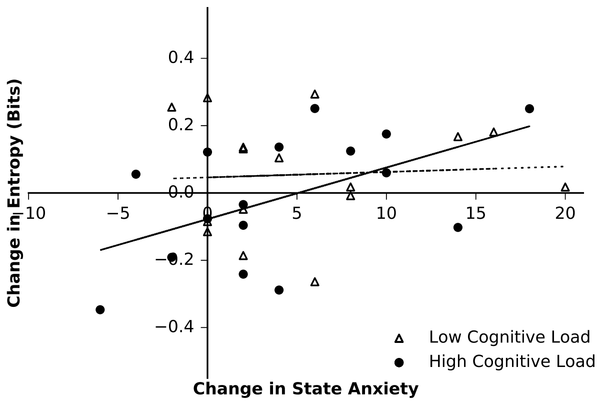

Figure 3: Regression lines showing the relationship between change in state anxiety and change in entropy, in high (solid line) and low cognitive load (dashed line) conditions

Gaze behavior Transition frequency and scanning entropy data are presented in Table 1. Analysis of transition frequency revealed a significant main effect for cognitive load, $F(1,15)$=22.78, p<.001,η_p^2=.60. Less transitions between AOIs were made in high cognitive load conditions. No significant main or interaction effects were found for scanning entropy data. However, Figure 3 shows the individual differences in reaction to the anxiety condition, and the moderating effect of cognitive load. Raghunathan and colleagues' statistic [27] revealed a significant difference between the correlations coefficients of change variables in high and low cognitive load conditions, z=1.72, p=.028. Linear regression analyses showed that ΔCognitive anxiety only significantly predicted ΔScanning entropy when cognitive load was high, b=.015, 95% CI[.001,0.3], t=2.32, p=.036, explaining 28% of the variance. Taken together, these results suggest that high cognitive load exacerbates the effects of state anxiety on the randomness of gaze behavior.

4 Discussion

The present study aimed to investigate how instrument scanning can be influenced by a user's state of anxiety and load. Participants trained to perform an instrument landing task in foggy conditions, where relevant information for task performance must be obtained from spatially separated cockpit instruments. Afterwards, during testing, both cognitive load and anxiety were manipulated. Increases in self-reported state anxiety and heart rate validated the effectiveness of the anxiety manipulation. Self-reported anxiety also increased during the high cognitive load conditions, suggesting that participants became more uncertain of their ability to successfully perform the task in such conditions. Results from the n-back matching task showed that cognitive load was successfully manipulated, with participants providing more incorrect responses in the 2-back condition. Reaction time remained constant across cognitive load conditions, which negates any concerns about a potential speed-accuracy trade-off. Interestingly, reaction time was quicker in anxiety conditions, with response accuracy remaining consistent. The most parsimonious explanation for this finding is that, in-line with previous research [23, 2], anxiety served a motivational function, leading to more on-task effort and an enhanced capability to expediently respond to the n-back task.

Previous investigations of scanning behavior across instrumented AOIs have focused on the information content and rate of presentation (e.g., [28, 29].These are factors that can be easily manipulated in visualization design. In contrast, the current work emphasises the importance of the user's psychological state in dictating changes in planned gaze behavior. High cognitive load was accompanied by a decrease in transitions between AOIs and, consequently, flight control performance deteriorated. This suggests that the sampling rate of information from the instruments was not sufficient to maintain performance. The current findings provide evidence to suggest that cognitive load may moderate the relationship between information seeking behavior and state anxiety. Specifically, only in high cognitive load conditions were individual responses to the anxiety manipulation positively related to changes in the randomness of gaze behavior. This finding is in-line with the predictions of ACT, and also supports interaction effects found in previous experiments [12, 13, 14].

Visualizations that are intended for use in high-anxiety, high-load environments should take note of the current findings. Although increasing the rate and channels of information presentation can deliver more information to the user, this remains limited by the user's ability to retrieve information efficiently and meaningfully with purposeful eye-movements. Cognitive load and anxiety can significantly limit a user's ability to seek out information, independent of a visualization's design. How many instrumented regions-of-interest can a user effectively scan, given the cognitive requirements and experienced anxiety of a given work environment? This is a concern that should factor into the design of an instrumented workstation. Future research should seek to formalize the cost-function of the factors (i.e, anxiety and cognitive load) that influence scanning efficiency. In doing so, we might be able to make informed decisions on the number of instruments that should be allowed for in a given workspace.

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References

[1] M. Corbetta and G.L. Shulman. Control of Goal-Directed and Stimulus-Driven Attention in the Brain. *Nature Reviews Neuroscience*, 3(3):215–229, 2002.

[2] M.W. Eysenck, N. Derakshan, R. Santos, and M.G. Calvo. Anxiety and cognitive performance: attentional control theory. *Emotion*, 7(2):336–53, 2007.

[3] N. Berggren and N. Derakshan. Attentional control deficits in trait anxiety: Why you see them and why you don't. *Biological Psychology*, 92(3):440–446, 2013.

[4] M. Behan and M.R. Wilson. State anxiety and visual attention: the role of the quiet eye period in aiming to a far target. *Journal of Sports Sciences*, 26(2):207–15, 2008.

[5] J. Causer, P.S. Holmes, N.C. Smith, and A.M. Williams. Anxiety, movement kinematics, and visual attention in elite-level performers. *Emotion*, 11(3):595–602, 2011.

[6] N. Nibbeling, R.R.D Oudejans, and H.A.M Daanen. Effects of anxiety, a cognitive secondary task, and expertise on gaze behav-

ior and performance in a far aiming task. *Psychology of Sport and Exercise*, 13(4):427–435, 2012.

[7] M.R. Wilson, S.J. Vine, and G. Wood. The influence of anxiety on visual attentional control in basketball free throw shooting. *Journal of Sport & Exercise Psychology*, 31(2):152–168, 2009.

[8] M.R. Wilson, G. Wood, and S.J. Vine. Anxiety, attentional control, and performance impairment in penalty kicks. *Journal of Sport & Exercise Psychology*, 31:761–775, 2009.

[9] L.J. Moore, Samuel J. Vine, A. Cooke, C. Ring, and M.R. Wilson. Quiet eye training expedites motor learning and aids performance under heightened anxiety: The roles of response programming and external attention. *Psychophysiology*, 49(7):1005–1015, 2012.

[10] J. Allsop and R. Gray. Flying under pressure: Effects of anxiety on attention and gaze behavior in aviation. *Journal of Applied Research in Memory and Cognition*, 3(2):63–71, 2014.

[11] S.J. Vine, L. Uiga, A. Lavric, L.J. Moore, K. Tsaneva-Atanasova, and M.R. Wilson. Individual reactions to stress predict performance during a critical aviation incident. *Anxiety, Stress, & Coping*, 28(4):467–477, 2015.

[12] N. Berggren, A. Richards, J. Taylor, and N. Derakshan. Affective attention under cognitive load: reduced emotional biases but emergent anxiety-related costs to inhibitory control. *Frontiers in Human Neuroscience*, 7(APR 2013):188, 2013.

[13] N.P. Kinrade, R.C. Jackson, and K.J. Ashford. Dispositional reinvestment and skill failure in cognitive and motor tasks. *Psychology of Sport and Exercise*, 11(4):312–319, 2010.

[14] S. Qi, Q. Zeng, Y. Luo, H. Duan, C. Ding, W. Hu, and H. Li. Impact of working memory load on cognitive control in trait anxiety: An ERP study. *PLoS ONE*, 9(11), 2014.

[15] R. Cox, M. Martens, and W. Russell. Measuring Anxiety in Athletics: The Revised Competitive State Anxiety Inventory-2. *Journal of Sport & Exercise Psychology*, 25(4):519–533, 2003.

[16] D.D. Salvucci and J.H. Goldberg. Identifying Fixations and Saccades in Eye-Tracking Protocols. *Proceedings of the Eye Tracking Research and Applications Symposium*, pages 71–78, 2000.

[17] V.A. Huemer, M. Hayashi, F. Renema, S. Elkins, J.W. McCandless, and R.S. McCann. Characterizing Scan Patterns in a Spacecraft Cockpit Simulator: Expert Vs. Novice Performance. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, 49:83–87, 2005.

[18] S.R. Ellis and L. Stark. Statistical dependency in visual scanning. *Human Factors*, 28(4):421–438, 1986.

[19] R. Gibb, R. Schvaneveldt, and R. Gray. Visual misperception in aviation: glide path performance in a black hole environment. *Human factors*, 50(4):699–711, 2008.

[20] R. Gray, G.A. Geri, S.C. Akhtar, and C.M. Covas. The role of visual occlusion in altitude maintenance during simulated flight. *Journal of Experimental Psychology: Human perception and performance*, 34(2):475–488, 2008.

[21] W.K. Kirchner. Age differences in short-term retention of rapidly changing information. *Journal of Experimental Psychology*, 55(4):352–358, 1958.

[22] M.J. Kane, A.R. Conway, T.K. Miura, and G.J. Colflesh. Working memory, attention control, and the N-back task: a question of construct validity. *J Exp Psychol Learn Mem Cogn*, 33(3):615–622, 2007.

[23] A. Cooke, M. Kavussanu, D. Mcintyre, I.D. Boardley, and C. Ring. Effects of competitive pressure on expert performance: Underlying psychological, physiological, and kinematic mechanisms. *Psychophysiology*, 48(8):1146–1156, 2011.

[24] A.M. Williams, J. Vickers, and S. Rodrigues. The effects of anxiety on visual search, movement kinematics, and performance in table tennis: A test of Eysenck and Calvo's processing efficiency theory. *Journal of Sport & Exercise Psychology*, 24(4):438–455, 2002.

[25] K. Vytal, B. Cornwell, N. Arkin, and C. Grillon. Describing the interplay between anxiety and cognition: From impaired performance under low cognitive load to reduced anxiety under high load. *Psychophysiology*, 49(6):842–852, 2012.

[26] C.M. Judd, D.A. Kenny, and G.H. McClelland. Estimating and testing mediation and moderation in within-subject designs. *Psychological Methods*, 6(2):115–134, 2001.

[27] T. E. Raghunathan, R. Rosenthal, and D.B. Rubin. Comparing correlated but nonoverlapping correlations. *Psychological Methods*, 1(2):178–183, 1996.

[28] J.W. Senders. The human operator as a monitor and controller of multidegree of freedom systems. *IEEE Transactions on Human Factors in Electronics*, HFE-5(1):2–5, 1964.

[29] C.D. Wickens, J. Helleberg, J. Goh, X. Xu, and W.J. Horrey. Pilot task management: Testing an attentional expected value model of visual scanning. Technical report, 2001.